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A comparative study of superheat utilization measures of extraction steam in double reheat power plants

Luyao Zhou[1], Gang Xu[1,2], Yongping Yang[1]*, Shifei Zhao[1], Cheng Xu[1], Kai Zhang[1]

1. Schoolof Energy Power and Mechnical Engineering, North China Electric Power University, Beijing 102206, China
2.Key Laboratory of Low-grade Energy Utilization Technologies and Systems of Ministry of Education of China, Chongqing University, Chongqing 400044, China

Abstract

The superheat degree of the regenerative extraction steam in double reheat systems is very high, leading to large temperature difference in the heat transfer process and worse thermal performance. This paper presents two typical systems to make the superheat of the extraction steam be used reasonably, which are a double reheat system with outer steam coolers and a double reheat system with a regenerative steam turbine. Thermodynamic analyses and techno-economic analyses are conducted to reveal the energy-saving effects of different systems. The results show that: the power generation efficiency of the system with outer steam coolers is increased by 0.16%-points than the conventional double reheat system, and the power generation efficiency of the system with a regenerative steam turbine can be further increased by 0.51%-points. Moreover, the cost of electricity of the system with a regenerative steam turbine is relatively lower than the system with outer steam coolers. This indicates that the two measures are both effective to use the superheat of the extraction steam. In addition, the system with a regenerative steam turbine is better than the system with outer steam coolers in both thermal and economic performance.

Keywords: double reheat, superheat, outer steam cooler, regenerative steam turbine, thermodynamic analysis, techno-economic analysis

1. Introduction

The parameter level of the ultra-supercritical (USC) units has rapidly developed worldwide. On a global scale, USC power generation technology is entering a fast-development stage. Thus, using the double reheat system is necessary to improve the thermal performance of USC units [1, 2]. The double reheat USC power plants has been identified by China as the key research and development project for the National "Twelfth Five-year Plan" [3]. The superheat degree of the regenerative extraction steam in double reheat systems is very high, leading to large temperature difference in the heat transfer process and worse thermal performance [4]. Over the past few decades, double reheat systems have received a considerable attention. For example, J. Yan et al. presented a detailed method for a mathematical model of double reheat system and conducted thermodynamic analysis on double reheat systems [5]. K.S. Reddy et al. made some researches on selecting appropriate reheat parameters for double reheat units [6]. However,

* Corresponding author. Tel.: +86-10-61772011.
E-mail address: yypncepu@163.com.

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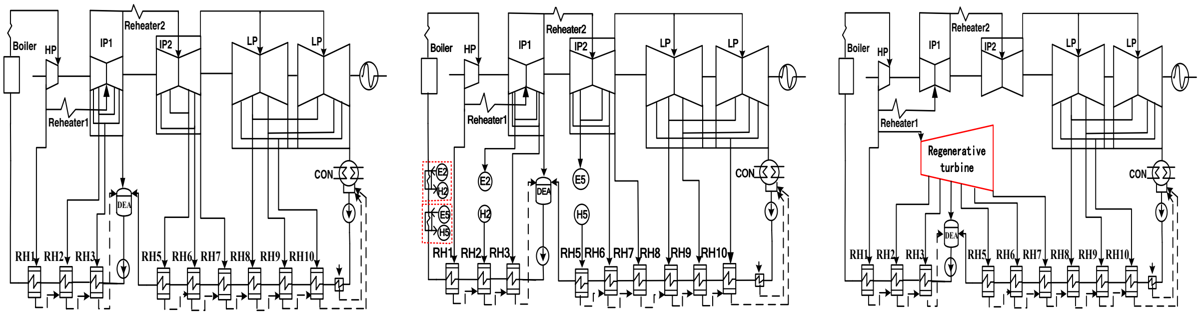
few studies focus on optimum utilization of extraction steam in double reheat power plants. In view of the importance of USC double reheat systems, studies on superheat utilization of extraction steam of double reheat systems in USC power plants are conducted in the paper. The objectives of the current study are as follows: (1) to present a double reheat system with outside steam coolers, (2) to present a double reheat system with a small regenerative steam turbine, (3) thermodynamic and techno-economic analyses of different systems are conducted to reveal the energy-saving effects of different systems.

2. Two superheat utilization measures of extraction steam in double reheat power plants

At present double reheat ultra-supercritical power generating units are still in research stage, there is no detailed data of double reheat system in ultra-supercritical power generating units. Through analysis of related literature, a typical double reheat system is presented as the Base Case. The main steam parameter is set to 30 MPa and 600 °C, and the reheat steam is heated to 610 °C. Fig. 1(a) illustrates a simplified process flow diagram of Base Case.

As mentioned earlier, the superheat degree of extraction steam after two reheat processes in double reheat systems is higher obviously. To reduce the superheat degree of extraction steam, this paper presents two typical systems to make the superheat of the extraction steam be used reasonably, which are a double reheat system with outer steam coolers (Case 1) and a double reheat system with a regenerative steam turbine (Case 2). Fig. 1(b) illustrates the simplified process flow diagram of Case 1. As shown in Fig. 1(b), two outer steam coolers are adopted to reduce the superheat degree of the 2# and 5# extractions, which are both located at the outlet of the 1# regenerative heater (RH) to improve the feed water temperature directly. To further reduce the superheat degree of the other extraction steam from intermediate pressure cylinder, Case 2 is proposed. Fig. 1(c) illustrates the simplified process flow diagram of Case 2. As can be seen from Fig. 1(c), the system draws the exhaust steam of high-pressure cylinder to a regenerative steam turbine, this part of steam will not enter the steam reheater of the boiler, directly into the regenerative steam turbine and then into regenerative heaters through extraction steam and exhaust steam.



(a) Base Case (b) Case 1 (c) Case 2

Fig. 1 Simplified process flow diagram of Base Case, Cases 1 and Case 2

3. Process Simulation and Performance Evaluation

In Case 1 and Case 2, the extraction steam pressure of the regenerative system is equivalent to the extraction steam pressure of the reference system. In this paper, EBSILON software is taken to simulate various systems [7]. In the different stages of the HP, IP, and LP turbines, the constant isentropic efficiencies are equal to 0.88, 0.91, and 0.87, respectively. The terminal temperature difference of the out steam cooler is set to 10 ^{o}C. The isentropic efficiency of the regenerative steam turbine is also specified. Based on the simulation results, analyses on thermodynamic performances of various systems are carried out. Based on the simulation results, analyses on thermodynamic performance of various systems are carried out.

The thermal performance results of different systems are derived from the simulation and calculation. Table 1 shows the comparison between the thermal performance and superheat degree of Base Case, Cases 1 and Case 2. The heat rate of Case 1 decreases by 26.2kJ/kWh compared with that of the Base Case. Besides, the power generation efficiency of Case 1 is 0.16%-points higher than that of Base Case. It can also be found that the heat rate in Case 2 decreases by 108.5kJ/kWh compared with that of Base Case. The power generation efficiency of the unit in Case 1 increases by 0.67%-points compared with that of Base Case. The reason lies in the reduction of the superheat degree and the reasonable utilization of extraction steam. Table 2 shows superheat degree of Base Case, Cases 1 and Case 2. It is also obvious to see that in Case 1, the superheat degree of 2# and 5# extraction steam is reduced, and the superheat degree of other extraction is not changed. However, the superheat degree of 2#-7# extraction steam in Case 2 is all significantly reduced.

Therefore, the two systems both can make utilization of the extraction steam superheat more reasonable and improve the heat transfer effect. In addition, the thermal performance of Case 2 is better than that of Case 1.

Table1. Thermal performance of cases

Performance index	Base Case	Case 1	Case 2
Heat Rate(kJ/kWh)	7687.4	7661.2	7578.9
Decrement(kJ/kWh)	——	26.2	108.5
Power Generation Efficiency (%)	46.83	46.99	47.5
Increment (%)	——	0.16	0.51
Coal Consumption (g/kWh)	262.65	261.76	258.95
Decrement(g/kWh)	——	0.89	3.7

Table2. Superheat of cases (^{o}C)

RH	Base Case	Case 1	Case 2
2#	276.7	37.9	82.5
3#	232.7	232.7	56.8
4#	184.1	184.1	24.9
5#	315.9	116.2	0
6#	270.4	270.4	0
7#	205.1	205.1	0

4. Techno-economic Analysis of different cases

With the two measures to optimize superheat utilization of extraction steam, new equipment and facilities will be added in power plants. This will lead to the investment of the power plant increase, and will bring with the increment in operation cost and maintenance cost. The specific techno-economic analysis of Base case, Case 1, Case 2 is conducted in this section.

The basic economic assumptions employed here include: (1) The assumed coal price, 4.09USD/GJ LHV, was the average cost for Chinese electric generators in 2012. It needs to be noted that China's coal price is higher compared to other countries, because of the high energy requirement and corresponding policies. (2) The exchange rate is set as 6.25 CNY/USD. (3) The annual utilization time is assumed to be 5000 hours per year. Table 3 gives the investment of added equipment.

Table 3 Investment of added equipment (million USD)

Equipment	Case 1	Case 2
outer steam coolers / regenerative steam turbine	1.60	4.32
Pipes	0.41	1.39
Construction cost	0.09	0.29
Total added investment	2.10	6.00

Standard portfolio analyses for electricity generation are normally performed using the COE [8], which is calculated by the sum of annual costs for a power generation system divided by the sum of annual energy production, which can be calculated as follows:

$$COE = \frac{[\text{Annual investment cost+Annual O\&M cost+Annual cost on fuel}]}{\text{Annual electricity production}}$$

Table 4 shows the results of the techno-economic performance of all the cases. It is clearly to see that: (1) compared to Base Case, the COE of Case 1 is reduced by 0.03 USD/MWh; (2) after adopting the regenerative steam turbine, the COE of Case 2 greatly decreases by 0.24 USD/MWh compared to that of Base Case.

Table 4 Techno-economic performance of cases

Performance index	Base Case	Case1	Case 2
Net efficiency of Plant (%)	46.83	46.99	47.5
Total plant investment (TPI, million USD）	743.50	745.60	749.50
Annual cost on fuel (million USD）	157.60	157.12	155.36
Annual investment capital cost (Cinv.million USD)	92.32	92.64	93.12
Operation and maintenance cost($C_{O\&M}$,million USD)	29.74	29.82	29.92
Cost of electricity (COE, USD/MWh）	55.92	55.89	55.68

5. Conclusions

This paper presents two typical systems to make the superheat of the extraction steam be used reasonably, which are a double reheat system with outer steam coolers and a double reheat system with a regenerative steam turbine. Besides, thermodynamic analyses and techno-economic analyses are conducted to reveal the energy-saving effects of different systems. The conclusions of this paper as follows:

(1) After adding outer steam coolers, the heat rate of Case 1 decreases by 26.2kJ/kWh compared with that of the Base Case. By adopting the regenerative steam turbine, the heat rate of Case 2 decreases by 108.5kJ/kWh compared with that of Base Case.

(2)Regardless of which operation conditions, the power generation efficiency of the two superheat utilization measures is both higher than that of the reference unit, and the power generation efficiency of Case 2 is the highest, followed by that of Case 1.

(3)In comparison, the COE of Case 1 is reduced after adding outer steam coolers. Furthermore, by adopting the regenerative steam turbine, the COE of Case 2 can be further decreased.

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